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A Heavily Boron-Doping Method for Fabrication of Thick MEMS Structural Layer

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Abstract: In MEMS devices, heavily boron-doped layers are usually used as structural layers. Due to the influence of solid solubility and concentration gradient in area near surface, the fabrication of a thicker layer(boron concentration $\geqslant 5\times10^{19}$ cm^{-3}) needs a longer diffusion duration. In order to fabricate the thicker layer under the same diffusion condition, multi-step diffusion method is put forth. It divides conventional diffusion process into two relatively short periods while maintaining the same cumulative diffusion duration. The two periods are performed continuously and each diffusion period includes one pre-deposition and one drive-in. Compared with conventional two-step diffusion method, this multi-step diffusion method can bring a larger quantity of boron dopants to silicon substrate and possesses the potential to trap dopants at a certain depth. Thus, it is possible to obtain thicker heavily boron-doped layers. In the experiment, a 21 μm thick heavily boron-doped layer was obtained by this method, 6 μm thicker than that obtained in references (less than 15 μm) using conventional two-step method under the same diffusion condition, which demonstrates that this method can fabricate thicker heavily boron-doped layers under the same diffusion condition.

Keywords: multi-step diffusion; heavily boron doping; structural layer fabrication

一种用于制备大厚度 MEMS 结构层的浓硼掺杂方法

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摘　要: 在 MEMS 器件中，浓硼掺杂层通常为器件的结构层. 但由于受表面固溶度及浓度梯度影响，该掺杂层(硼原子浓度$\geqslant 5\times10^{19}$ cm^{-3})厚度越大所需的扩散时间越长. 为了能在同等扩散工艺条件下，制备出更厚的浓硼掺杂层以满足器件要求，提出了多步扩散法. 即在保证总的累计扩散时间不变的前提下，将传统的扩散过程分为两个相对短的扩散周期. 并且这两个周期连续进行，每个周期各包含一次预扩散和再分布. 与传统的两步扩散相比，多步扩散法可为硅基底引入更大量的硼杂质，并且具有一定能力使硼杂质留在一定深度范围内. 因此该方法可以获得更大的有效节深. 实验中采用该方法成功制备出 21 μm 厚的浓硼掺杂层. 然而在文献中提到的采用传统两步法在同样条件下得到的厚度则小于 15 μm. 从而验证了该方法可在同等扩散工艺条件下，可以制备出更厚的浓硼掺杂层.

关键词: 多步扩散法; 浓硼掺杂; 结构层制备

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Various sensitive structures, such as thin layers and cantilevers, used in silicon micro sensors are mostly fabricated by bulk-silicon micromachining. In the manufacturing process of high-precision microstructures, self-stopped etching technique is usually adopted to obtain a heavily-doped layer as structural layer. Many micro devices have been fabricated using this technique, such as refractive silicon micro lens array, membrane of capacitive micro-silicon pressure sensor and atomic force microscope probe tips[1-3]. And in the manufacturing process of this layer, boron diffusion is a critical step. Its difficulty is to obtain a heavily boron-doped layer whose boron concentration should be no less than 5×10^{19} cm^{-3}[4], a prerequisite for self-stopped etching technique. At present, the universal method in doping process is two-step diffusion, in which predeposition and drive-in are performed only once, respectively. Predeposition is constant-surface-concentration diffusion which provides boron dopants in the whole process. Drive-in is constant-total-dopant diffusion, propelling boron dopants deep into silicon substrate. Both steps follow the Fick's law. If a thicker heavily boron-doped layer is desired, usual solution is to elevate temperature and extend diffusion duration, which is inefficient and energy-consuming and lowers layer depth uniformity[5]. Although elevating diffusion temperature can obtain thicker heavily doped layer at equal duration, SiC furnace tube, a kind of prohibitively expensive device, is indispensable for this solution. Therefore, it would be considerably promising to be able to obtain the same or even thicker layer using quartz furnace tube at the equal or even shorter diffusion duration. A multi-step diffision method is thus proposed in this paper.

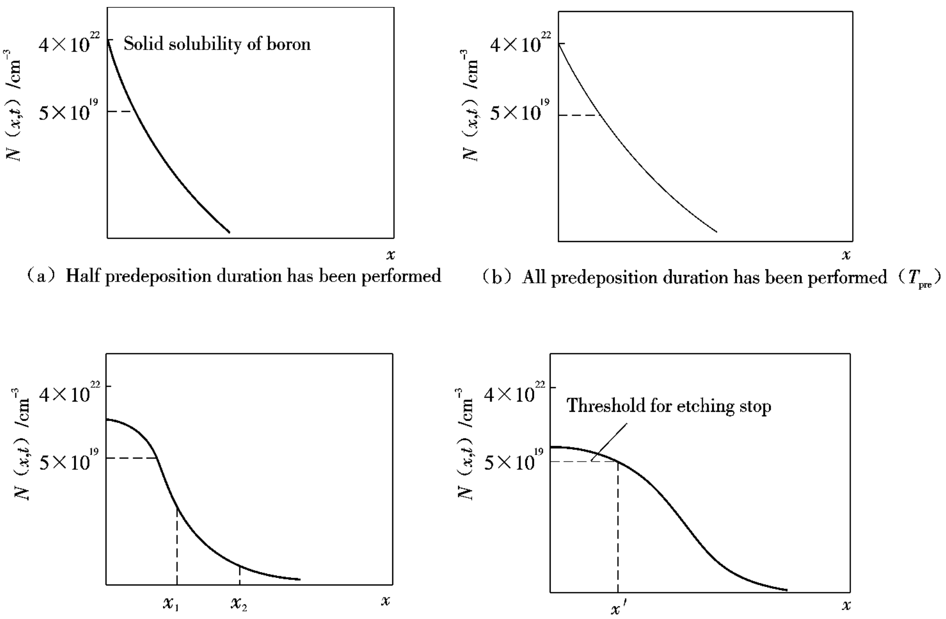
1 Differences between two methods

First of all, conventional method is not effective enough to obtain a huge quantity of dopants. According to Fick's first law, current density is proportional to dopant concentration gradient[6]. At the beginning of predeposition, current density is large due to sheer concentration gradient. It means that a great quantity of boron dopants can easily swarm into silicon substrate. But it falls with the advance of predeposition, for the gradual increase of dopant concentration in silicon substrate drops concentration gradient. This is more obvious in area near the surface, and will considerably retard the diffusion process from boron source to silicon substrate. Therefore, the total quantity of boron dopants will be influenced.

In the process of heavily boron doping, the quantity of boron dopants is a critical thing. And only when there are enough boron dopants can layer with desired thickness possibly be obtained. What's more, conventional method also fails to help to trap dopants in the certain layer with desired thickness. In the process of drive-in, there are no other extra factors to help to retard the decrease of dopant concentration in the desired depth. Therefore, the dopant concentration curve which follows Gaussian distribution tends to become gentle more quickly.

Aiming to improve the shortcomings in conventional method, the multi-step diffusion process is put forward, which divides conventional method into two periods. Each period includes one short predeposition and one short drive-in. As recited above, current density is proportional to dopant concentration gradient, and it decreases with the fall of dopant concentration gradient in silicon substrate, consequently retarding diffusion process. In other words, concentration gradient is the driving force of dopants diffusion. Thus, increasing concentration gradient in the diffusion process can be a good option for obtaining a huge quantity of dopants which is the prerequisite for thick heavily doped layer fabrication.

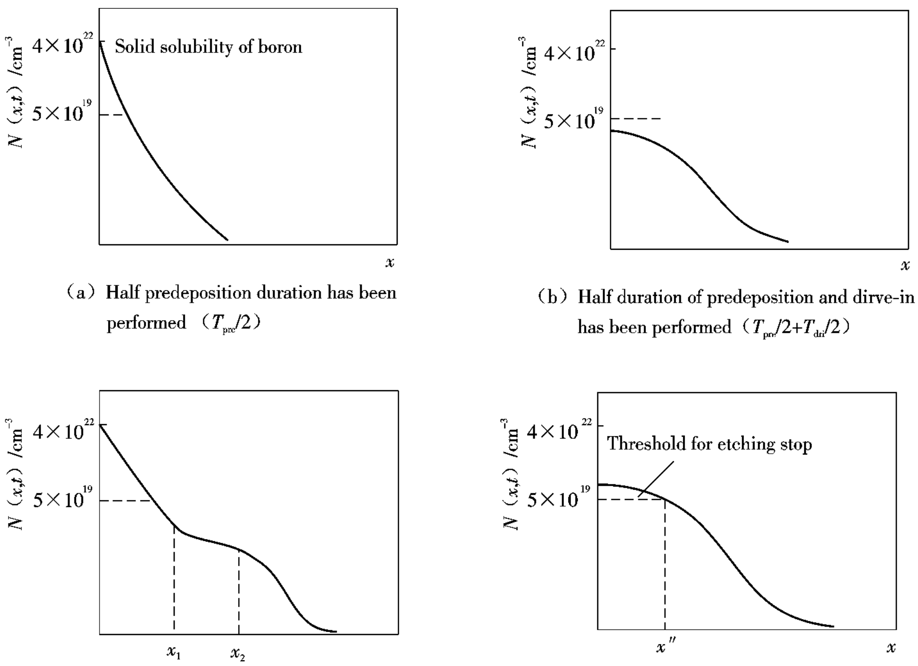
Even though it is difficult to provide a quantitative explanation for the variation of dopant concentration in multi-step diffusion at present, two groups of schematic diagrams (Figs. 1—2) are still put forward to point out the differences. In multi-step diffusion, the duration of predeposition (T_{pre}) is divided into two short ones (T_{pre1} and T_{pre2}), as is that of drive-in process. The drive-in process in the first period (T_{dri1}) would dramatically reduce dopant concentration in silicon substrate, especially in area near the surface, providing a relatively lower substrate concentration for the following process (T_{pre2}). Comparing the equal remaining duration of predeposition in Fig. 1(a) and Fig. 2(b), it is very obvious that silicon substrate in Fig. 2(b) would possess much lower concentration in area near the surface. Consequently, predeposi-



（a）Half predeposition duration has been performed　（b）All predeposition duration has been performed（T_{pre}）

（c）Half drive-in duration has been performed　（d）Final concentration curve（$T_{pre}+T_{dri}$）

Fig. 1　Schematic diagram of conventional two-step diffusion method



（a）Half predeposition duration has been performed（$T_{pre}/2$）　（b）Half duration of predeposition and dirve-in has been performed（$T_{pre}/2+T_{dri}/2$）

（c）Predeposition and half drive-in duration has been performed（$T_{pre}/2+T_{dri}/2$）$+T_{pre}/2$　（d）Final concentration curve（$T_{pre}/2+T_{dri}/2$）+（$T_{pre}/2+T_{dri}/2$）

Fig. 2　Inferred schematic diagram of the novel multi-step diffusion method

tion in the second diffusion period (T_{pre2}) possesses larger concentration gradient and greater current density, which can bring a larger quantity of boron dopants, laying a solid foundation for the final drive-in process (T_{dri2}). What's more, when only half drive-in duration remains, the concentration curve should be like Fig. 2(c), which tends to be more like a combination of complementary error distribution and Gaussian distribution. The qualitative difference of substrate concentration is shown in Fig. 1(c) and Fig. 2(c). Because substrate concentration at a certain depth has been elevated in the first period, the concentration curve in a certain zone, like x_1 to x_2 in Fig.

2(c), will be much higher than that in Fig. 1(c). It considerably retards dopants that swarm into substrate in the second period diffusing deep into substrate. Consequently, most of these dopants tend to perform the final drive-in process at a relatively limited depth. Therefore, the multi-step diffusion method possesses the potential to obtain a thicker heavily boron-doped structural layer. The difference can be clearly figured out from Fig. 2(d) and Fig. 1(d), in which x'' and x' represent the expected layer depth obtained from novel and conventional method, respectively.

2 Experimental results

In order to prove the theoretical analysis and estimation, the verification experiment was performed, whose detailed parameters are shown in Tab. 1. The diffusion duration is selected as close to that mentioned in Refs. [5] and [7] as possible, so that authoritative records can be easily obtained as contrasts.

Tab. 1 Thermal diffusion parameters

Diffusion period	Temperature/℃		Duration/h	
	Predeposition	Drive-in	Predeposition	Drive-in
First diffusion period	1 030	1 150	8	25
Second diffusion period	1 030	1 150	7	15

The boron source used in experiment is boron glass-ceramics (PWB-2), and single-side diffusion is adopted (Fig. 3). The 4 inch silicon wafers used are p-type (100), double-side polished and 400 μm in thickness. The boron-silicate-glass (BSG) was removed after all the diffusion periods had been performed. The average surface resistance is 203.7 mΩ/□, which was measured from ten points selected regularly (Fig. 4). Then the silicon wafers were cut into small samples (Fig. 5). Each sample contains six cells, in which 3.05 mm square etching-windows are marked as gray and the SiO_2 cover is marked as black. This cover was fabricated by thermal oxidization. The following process is self-stopped etching that was performed in 25% TMAH solution at 85 ℃ and lasted for 13 h. After that, the heavily boron-doped layer was finally obtained (Fig. 6(a), (c)) and surface photograph is shown in Fig. 6(b). In order to obtain the sections, membranes were incised and their thicknesses were measured by scanning electron microscope (SEM) (Fig. 6(d)). The maximum and minimum thickness is 20.99 μm and 20.54 μm, respectively (Fig. 7), so the thickness uniformity is less than 0.5 μm, indicating excellent concentration uniformity.

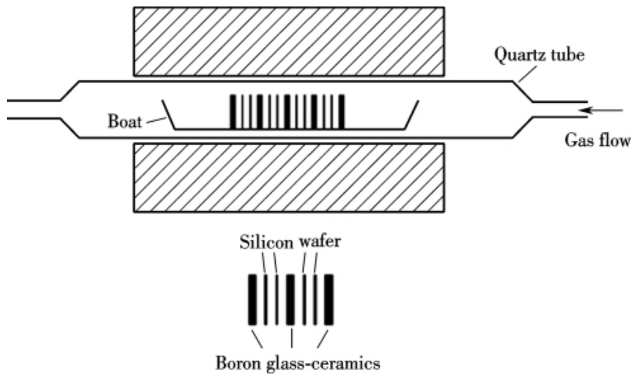


Fig. 3 Schematic diagram of single-side diffusion

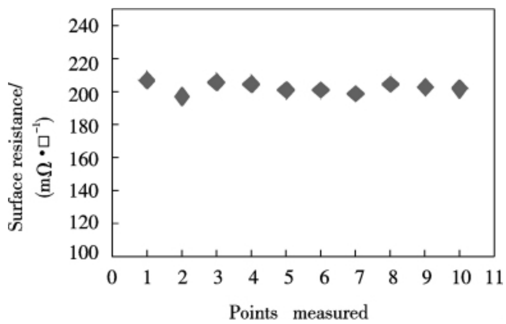


Fig. 4 Surface resistance of the layer

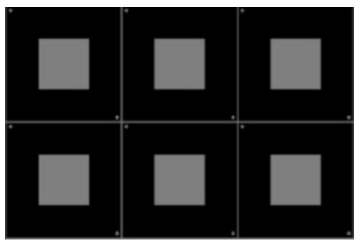
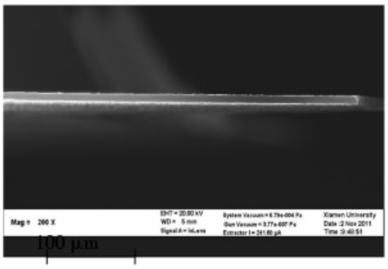
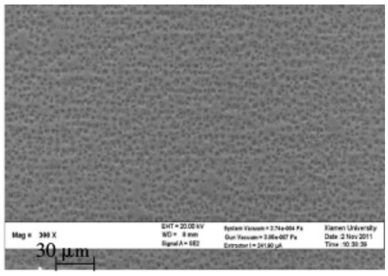


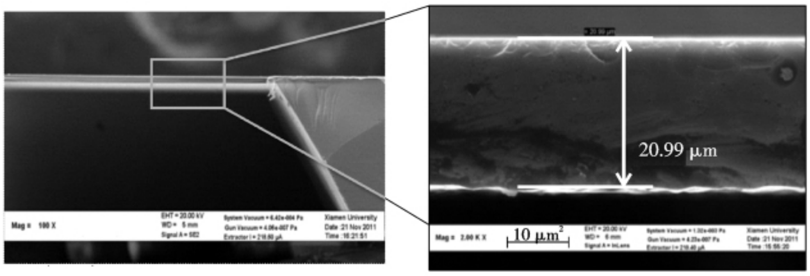
Fig. 5 CAD diagram of etching specimen



(a) Cross-section diagram



(b) Surface



(c) Cross-section diagram from other perspectives (d) Thickness measured

Fig. 6 SEM photograph of the fabricated structural layer

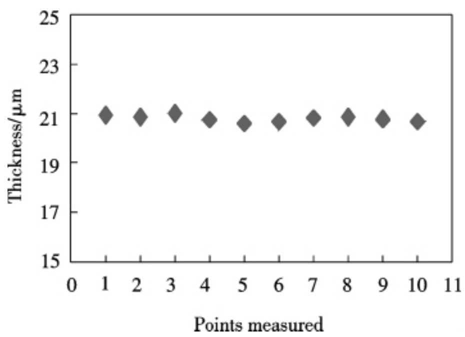


Fig. 7 Thickness of the layer

The experimental results are consistent with the former analysis and estimation. In the experiment, heavily boron-doped layer that is 21 μm in thickness was obtained, while the layer thickness mentioned in Refs. [5] and [7] is only 12 μm and 14 μm, respectively, using conventional method. The specific experimental parameters of the references and ours are shown in Tab. 2.

Besides, the diffusion type adopted in this experiment is single-sided, which demonstrates that the heavily boron-doped layer obtained by single-side diffusion would be dramatically thinner than that obtained by double-side diffusion using conventional method[2]. Nevertheless, the layer obtained by multi-step diffusion is obviously thicker than that mentioned in Ref. [4], and the surface resistance is much lower as well, indicating higher boron concentration near the surface.

Tab. 2 Thickness of heavily boron-doped layer

Data source	Experimental parameters and results						
	Temperature/℃		Duration/h		Surface resistance/(mΩ·□$^{-1}$)	Diffusion type	Layer thickness/μm
	Predeposition	Drive-in	Predeposition	Drive-in			
Ref. [5]	1 030	1 170	15	60.0	Not mentioned	Single-side	12
Ref. [7]	1 050	1 180	25	37.5	510	Double-side	14
Our results	1 030	1 150	15	40.0	203.7	Single-side	21

Note: In Refs. [5] and [7], boron glass-ceramics (PWB-2) are used as boron source and traditional diffusion method is adopted.

3 Conclusion

It is demonstrated experimentally that multi-step diffusion possesses the potential not only to obtain a huge quantity of dopants but also to retard dopants diffusing deep into the substrate. So, it could be a novel solution to the fabrication of heavily boron-doped structural layer with great thickness, which is universally used in various sensitive structures of micro sensors. The further study aims at obtaining the exact dopant concentration curve in multi-step diffusion through theoretical and experimental analysis for the further understanding of inherent mechanism.

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